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Triodyne Inc.
Consulting Engineers & Scientists – Safety Philosophy & Technology
666 Dundee Road, Suite 103, Northbrook, IL 60062-2702
(847) 677-4730 FAX: (847) 647-2047
e-mail: infoserv@triodyne.com
www.triodyne.com

Infant Pull Strength - Ability to Dislodge Crib Sheets

By Ralph L. Barnett* and Dennis B. Brickman, P.E.**

ABSTRACT

The suffocation of infants caused by crib sheet entanglement appears to be a nonproblem which has nevertheless resulted in a brouhaha that has incited remediation activities by the Good Housekeeping Institute (GHI), American Society of Testing Materials (ASTM), Consumer Product Safety Commission (CPSC), Juvenile Products Manufacturers Association (JPMA), crib sheet manufacturers, and product liability support professionals of different stripes. To show that the removal of crib sheets by infants is not a safety issue, one may establish that the problem is not reasonably foreseeable. Three approaches for doing this are described in this paper: anecdotal, simulation, and reliability. The reliability of a crib sheet is the probability that it will remain in situ when exposed to the community of infants. Application of the classical "load minus strength" analysis required new information on the pull strength of infants.

INTRODUCTION

On May 8, 1998, a 12 month old boy died of asphyxiation during his afternoon nap in the crib shown in Fig. 1 outfitted with a mattress of 12.4 cm (4.875 in.) depth and a fitted crib sheet with typical elastic edging. The parents of the infant boy filed a wrongful death lawsuit alleging that he was able to pull the crib sheet off the mattress which wrapped around him and suffocated him. This case has been the focus of media coverage; the infant's family members have been interviewed by several local television stations and they have appeared on the NBC news show "Dateline". Also, "Good Housekeeping" magazine has run two stories about the alleged dangers of fitted crib sheets that featured the child's mother. The boy's mother herself has subsequently designed a "pillowcase" type crib sheet secured by a hook and loop strip at the opening (Ref. 1).

In conjunction with their magazine articles, the Good Housekeeping Institute embarked on the development of a safety standard for fitted infant crib sheets. An early proposed standard was offered on November 24, 1998 which focused on the four corners of the mattress/crib sheet system where a vertical force and an angled force at 45° (side-to-side and top-to-bottom) are applied toward the inside of the crib (Ref. 2). A single crib sheet appropriately laundered in accordance with the AATCC Test Method 150-1995, "Dimensional Changes in Automatic Home Laundering of Garments" (Ref. 3), gave rise to eight peak force (resistance) values required to pull the sheet off the mattress corners. As part of the test protocol, a 9.1 kg (20 lb) container of sand simulating an infant's weight

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* Professor, Mechanical & Aerospace Engineering, Illinois Institute of Technology, Chicago, IL; Chairman, Triodyne Inc., Northbrook, IL

** Senior Mechanical Engineer, Triodyne Inc., Northbrook, IL.

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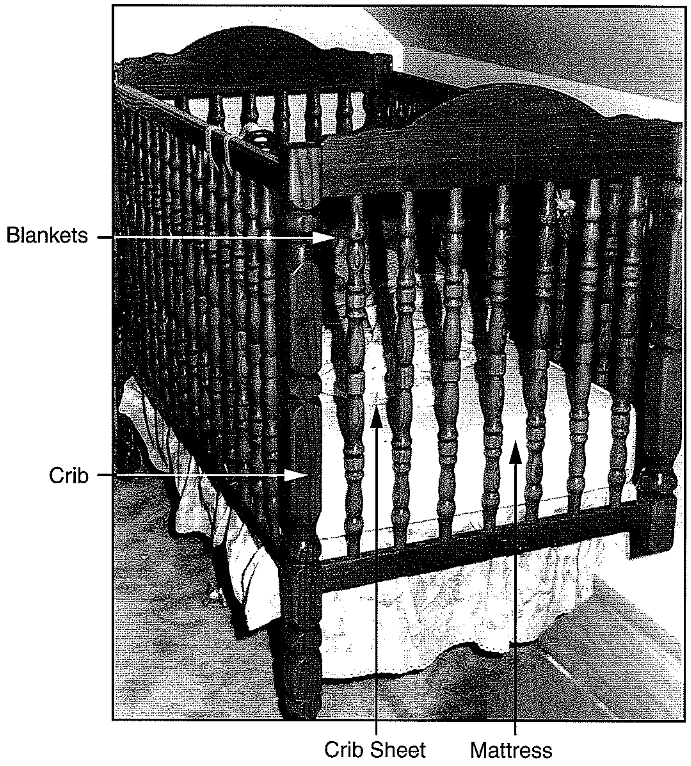

Figure 1 - Police Photograph of Subject Crib

was placed onto the mattress centered width-wise and located a third of the mattress length from the end being tested. If the lowest resisting force of the eight readings was equal to or greater than 44.5 *N* (10 lb), then the sheet-under-test passes the GHI test for a 15.2 cm (6 in.) thick standard mattress covered with a fitted mattress pad and supported in a standard crib having inner dimensions of 71.1 ± 1.6 cm (28 ± 0.625 in.) by 133.0 ± 1.6 cm (52.375 ± 0.625 in.) as per CFR 1508.3 (Ref. 4).

The development of the fitted crib sheet standard test method and procedure was initiated by GHI on August 26, 1998 (Ref. 5). Between August 26, 1998 and May 5, 2003, there have been nine proposed drafts. The challenge of making a standard that reflects real-life circumstances is daunting because so many variables are encountered that affect the friction resistance of the crib sheets. For example:

- Mattress thickness (4, 5, 6 inches)
- Mattress weight
- Mattress material
- Mattress construction (foam, innerspring)
- Mattress Cover/Pad
- Bumper pad
- Mattress support (furniture grade plywood, smooth plastic laminates, wood planks, metal grids)
- Number of sheet washings
- Method of washing sheets
- Rate of pull
- Pull direction (vertical, 45 degree angle side-to-side and top-to-bottom)
- Pull persistence (10 seconds)
- Weight of infant (e.g. 20 pounds)
- Infant's position in crib
- Fitting the sheet to the mattress
- Atmospheric conditions

These variables and more have all been identified and considered by the framers of the proposed standard which has been continuously evolving. One of the most critical features of the proposed deterministic standard is the go/no-go criterion of 44.5 *N* (10 lb) which is supposed to reflect the pull strength of infants. No testing was performed to establish this applied loading; instead, the GHI appealed to their toy requirements and procedures for ages zero to eighteen months (Ref. 6). This matter will be studied in this paper.

CRIB SHEET ACCIDENT STATISTICS — ANECDOTAL

CPSC Crib Sheet Accident Statistics

According to the Consumer Product Safety Alert on Crib Sheets, since 1984 the U.S. Consumer Product Safety Commission (CPSC) has learned of the deaths of 17 babies, most under 12 months old, who suffocated or strangled primarily when they became entangled in sheets in their cribs or beds (Ref. 7). However, only two of these deaths related to fitted crib sheets. In light of these anecdotal accident statistics, on November 4, 1997, the Section F15.19 Infant Bedding Subcommittee questioned whether or not the issue of a fitted crib sheet coming off the mattress resulting in a suffocation should be addressed (Ref. 8).

Case Analysis

In the subject case involving the 12 month old boy, one of the two relevant accidents, police officers found an afghan and a quilt in the crib immediately following the accident as depicted in Fig. 1. The infant bedding safety literature is replete with admonitions made by CPSC, the American Academy of Pediatrics (AAP), the National Institute of Child Health and Human Development (NICHD), the Juvenile Products Manufacturers Association (JPMA), and other safety organizations that infants should not be put to sleep in a crib with quilts, comforters, and blankets (Refs. 9-19). The medical literature discusses the association between the use of soft infant bedding and the increased risk of Sudden Infant Death Syndrome (SIDS) (Refs. 20-24). Given the circumstances surrounding the subject incident involving the 12 month old boy, it is inconclusive that the fitted crib sheet was the instrumentality associated with the infant fatality.

The second accident, which occurred on November 21, 1996 in Phoenix, Arizona, involves a 7 month old male. According to the CPSC narrative, "Fitted full size crib mattress sheet wrapped so tightly around rib cage that chest could not expand to breathe. Victim was able to pull free a corner of the sheet and then rolled into it." This reference is insufficient for determining whether human error or the design of the fitted crib sheet caused this unfortunate incident.

Accident Frequency Rate

One of the most important measures of risk is the accident frequency rate (AFR) which is defined as the number of disabling injuries per million hours of exposure (Ref. 25). It is projected that the number of fitted crib sheets sold from 1988 to 1998 by the U.S. crib sheet manufacturer with the largest market share is 20.4 million sheets. Using conservative assumptions for crib sheet usage (10 hours per day) and life (50 days), yields a total usage of 10,200 million hours. Therefore, the accident frequency rate for the subject crib sheet manufacturer is: 1/10,200 = 0.0000980. Comparing this accident frequency rate to the lowest recorded AFR for the "all industries" category (5.99), we get 5.99/0.0000980 = 61,098.

The conclusion to be drawn from the accident frequency rate analysis is that the suffocation of infants caused by fitted crib sheet entanglement is not foreseeable and is consequently a nonproblem.

SIMULATION

Crib-Sheet System Test Setup

Figure 2 depicts the crib sheet system setup utilized during the simulation testing of the subject 12 month old boy's accident. An exemplar 100% cotton sheet was laundered five times in accordance with AATCC Test Method 150-1995. Metal grommets were inserted in the four corners of the sheet. Colored plastic toy rings were attached to the metal grommets at each corner of the sheet. Then the sheet was fitted over an exemplar crib mattress such that the toy rings rested on top of the sheet at the four corners. The crib was situated on carpeting in a laboratory setting with curtains utilized to simulate the size of an infant's bedroom. A video camera with a wide angle lens was mounted above the crib and a monitor was placed behind one of the curtains.

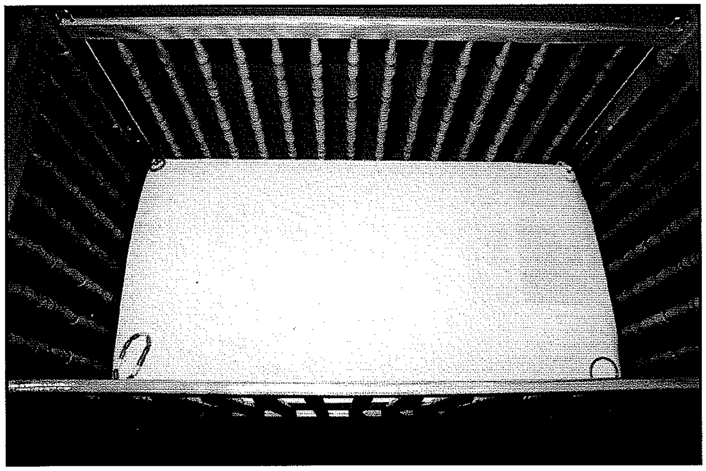

Figure 2 - Crib Sheet Simulation Testing Setup

Infant Test Subjects

Table 1 displays the gender, age, weight, and height of the infant test subjects who participated in the simulation. The ages of these 33 infant subjects ranged from 11 to 15 months. Advertisements were placed in local newspapers to recruit the infant subjects.

Test Protocol

The test program was conducted during daytime hours when the infant subjects were fully awake and alert. The infant subjects were placed in the crib and encouraged by their caregivers to pull on the rings affixed to the four corners of the sheet in order to pull the sheet off the mattress. The caregivers manipulated the rings and gave verbal pull commands to the infant subjects to attract them to the rings. In addition, the infant subjects were given time alone in the crib while their caregivers monitored their activities from behind the curtain.

Test Results

All 33 infant subjects participated in the simulation by gripping and pulling on the rings. Table 1 displays the number of attempts each infant subject made in order to pull the fitted crib sheet off the mattress. The test results indicate that the crib sheet was not pulled off the mattress by the infant subjects during 358 attempts with a cumulative exposure of 3 hours and 10 minutes.

CRIB SHEET RELIABILITY

Recognizing that the resistance of crib sheets depends on friction which is a stochastic phenomenon [26], the problem of crib sheet removal can be formulated as a conventional reliability problem. The reliability of a crib sheet is the probability that it will remain in situ when exposed to the community of infants. It can be calculated using the statistical distributions of resistance and pull strength.

Crib Sheet Resistance

Using the test protocol described in general terms in the introduction, GHI tested 23 popular crib sheets; only one passed the vertical pull test with its lowest peak resistance at 46.5 *N* (10.46 lb). Two sheets passed the 45° angle pull test. The strongest crib sheet, GHI No. 2, was then subjected to a repeatability test where one corner was tested ten times; the various values of pull resistance r measured by GHI are tabulated in Table 2.

It should be observed that none of the test results were as high as 44.5 *N* (10 lb). Consequently, crib sheet No. 2 failed the GHI test which means that all 23 of the popular crib sheets failed the proposed GHI standard.

Table 1 - Infant Crib Sheet Test Log

Subject No.	Gender	Age (months)	Weight kg (lb)	Height cm (in.)	Horizontal Pull Force N (lb)	Ring Pull Attempts	Grabbed Sheet
1	F	11	7.7 (17)	71.1 (28)	9.8 (2.2)	5	N/A
2	F	11	7.7 (17)	71.1 (28)	2.2 (0.5)	7	N/A
3	M	11	8.6 (19)	69.9 (27.5)	7.1 (1.6)	16	N/A
4	F	11	9.1 (20)	69.9 (27.5)	7.6 (1.7)	17	NO
5	F	11	9.1 (20)	76.2 (30)	6.2 (1.4)	1	NO
6	F	11	9.5 (21)	71.1 (28)	4.9 (1.1)	14	N/A
7	F	11	9.5 (21)	72.4 (28.5)	7.1 (1.6)	7	NO
8	M	11	9.5 (21)	76.2 (30)	4.4 (1.0)	17	N/A
9	F	11	10.4 (23)	72.4 (28.5)	—	13	NO
10	M	11	10.4 (23)	78.7 (31)	5.8 (1.3)	13	N/A
11	M	11	10.9 (24)	77.5 (30.5)	12.9 (2.9)	6	N/A
12	M	11	10.9 (24)	77.5 (30.5)	10.2 (2.3)	19	NO
13	M	12	9.1 (20)	73.7 (29)	3.1 (0.7)	27	NO
14	F	12	9.3 (20.5)	73.7 (29)	8.0 (1.8)	4	N/A
15	F	12	10.0 (22)	76.2 (30)	11.1 (2.5)	6	NO
16	F	13	9.1 (20)	74.9 (29.5)	2.7 (0.6)	15	N/A
17	M	13	9.5 (21)	71.1 (28)	2.2 (0.5)	12	NO
18	F	13	10.0 (22)	74.9 (29.5)	8.9 (2.0)	12	NO
19	F	13	10.0 (22)	77.5 (30.5)	6.7 (1.5)	7	N/A
20	M	13	10.4 (23)	73.7 (29)	4.9 (1.1)	13	N/A
21	M	13	10.4 (23)	78.7 (31)	—	6	NO
22	F	13	11.3 (25)	78.7 (31)	4.4 (1.0)	4	NO
23	M	13	11.3 (25)	81.3 (32)	4.9 (1.1)	5	YES
24	M	13	11.8 (26)	78.7 (31)	17.3 (3.9)	27	N/A
25	M	14	9.1 (20)	72.4 (28.5)	10.7 (2.4)	17	NO
26	M	14	9.5 (21)	78.7 (31)	7.6 (1.7)	12	N/A
27	F	14	9.8 (21.5)	74.9 (29.5)	—	7	NO
28	F	15	9.5 (21)	76.2 (30)	11.1 (2.5)	17	YES
29	F	15	10.4 (23)	80.0 (31.5)	3.6 (0.8)	5	YES
30	M	15	11.3 (25)	78.7 (31)	4.0 (0.9)	6	NO
31	F	15	11.8 (26)	80.0 (31.5)	3.6 (0.8)	8	NO
32	F	15	12.7 (28)	82.6 (32.5)	—	9	N/A
33	M	15	12.7 (28)	83.8 (33)	6.2 (1.4)	4	N/A

Table 2 - GHI Repeatability Pull Tests - Crib Sheet No. 2

Test Number	Vertical Pull Force (lb)
1	8.5
2	8.3
3	7.9
4	7.8
5	7.7
6	7.2
7	7.4
8	7.2
9	7.7
10	7.2
Average Pull Force	7.7
Standard Deviation	0.4

Infant Pull Capability - Literature

Quoting the Associate Engineering Director of GHI and key architect of the GHI test procedures for fitted crib sheets, "After extensive research, we discovered that the industry lacked in studies and statistics addressing the strength of pull forces attributable to infants, and the pull force required to lift a corner of a fitted crib sheet. We could only refer to data available from a standardized toy-safety test (that of ASTM's F963-95—Standard Consumer Safety Specification on Toy-Safety, section 8.9.1.1)." The authors of the present paper also failed to uncover basic pull strength data for infants.

The ability of newborns to maintain a claw-like power grip often allows them to support their weight when grasping an adult's horizontally disposed fingers. On the other hand, they cannot begin to "chin" themselves even at the age of twelve months. The power grip is an interference phenomenon that always generates a greater resistance than a pinching action which is a friction concept. For example, the tugging force on a sheet is limited by the pinch resistance which is twice the product of the pinch force and the friction coefficient of the finger/sheet couple. An attempt was made to directly measure the pinch resistance of infants.

Pinch Resistance - Infants

Figure 3 shows the crib with fitted sheet setup utilized during the infant pinch resistance test program. An exemplar 100% cotton sheet was laundered five times in accordance with AATCC Test Method 150-1995. An opening was cut into the top of the mattress in one corner. A cellular phone and a small object chosen by the infant test subject were placed in the mattress interior. Then the crib sheet was fitted over the crib mattress. The infant test subjects listed in Table 1 were placed in the crib and the sheet was pulled off one corner of the mattress, exposing the cellular phone and small object placed in the mattress interior. The infant test subjects were allowed to retrieve the cellular phone and small object from the mattress interior one time. Then the cellular phone and small object were replaced into the interior of the mattress and the exposed mattress corner was recovered by the sheet. The cellular phone was set to both ring and vibrate during the duration of the testing. The infant test subjects were encouraged to pinch the sheet and pull it off the mattress in order to retrieve the cellular phone and small object situated in the mattress interior. In addition, the infant subjects were given time alone in the crib while their caregivers monitored their activities from behind the curtain. The pinch resistance testing was videotaped from a perspective looking down on the crib. In contrast to the simulation using toy rings mounted on top of the crib sheet corners where there was 100% participation of the infant subjects, the results of the pinch resistance testing are mixed. It is very difficult to entice infants ranging from 11 to 15 months old to attempt to pinch the sheet corner and pull the crib sheet off the mattress. In general, the infants' interest was highest at the beginning of the test when the sheet initially covered the exposed corner of the mattress. Only 3 of the 33 infant subjects pinched the sheet and attempted to pull it off the mattress, but they were unsuccessful. Fifteen of the infants attempted to grab the top of the sheet, but they were unable to get a firm grip. Finally, the remaining 15 infants did not even attempt to grab the crib sheet at all (designated as N/A on Table 1). None of the 33 infant subjects were able to pinch the crib sheet and pull it off the mattress during a cumulative exposure of 2 hours and 38 minutes.

Horizontal Arm Pull Testing

Figure 4 illustrates the test setup utilized in the infant horizontal pull test program. A strip was taken from an exemplar 100% cotton crib sheet. A metal grommet was inserted at one end of the sheet. A Chatillon DFG-100 digital force gauge was attached to the metal grommet in the sheet. A toy ring was attached to the free end of the sheet strip. The infant subjects listed in Table 1 were placed in a seated position on carpeting and were encouraged to pull horizontally on the ring while a technician held the digital force gauge steady. The maximum horizontal pull force values are recorded in Table 1. It should be noted that 29 of the 33 infant subjects participated in the arm pull testing. Their associated pull strengths p are fitted with a normal probability density distribution in Fig. 5. The maximum horizontal pull force recorded for all infant subjects was 17.3 N (3.9 lb) corresponding to infant subject number 24. The average pull force value was $\overline{p} = 6.873N(1.545\,\mathrm{lb})$ with a standard deviation of $\sigma_p = 3.554N(0.7989\,\mathrm{lb})$.

Following conventional reliability protocol (Ref. 27), the reliability of a fitted crib sheet R is the probability that its resistance r is equal to or greater than the applied loading p;

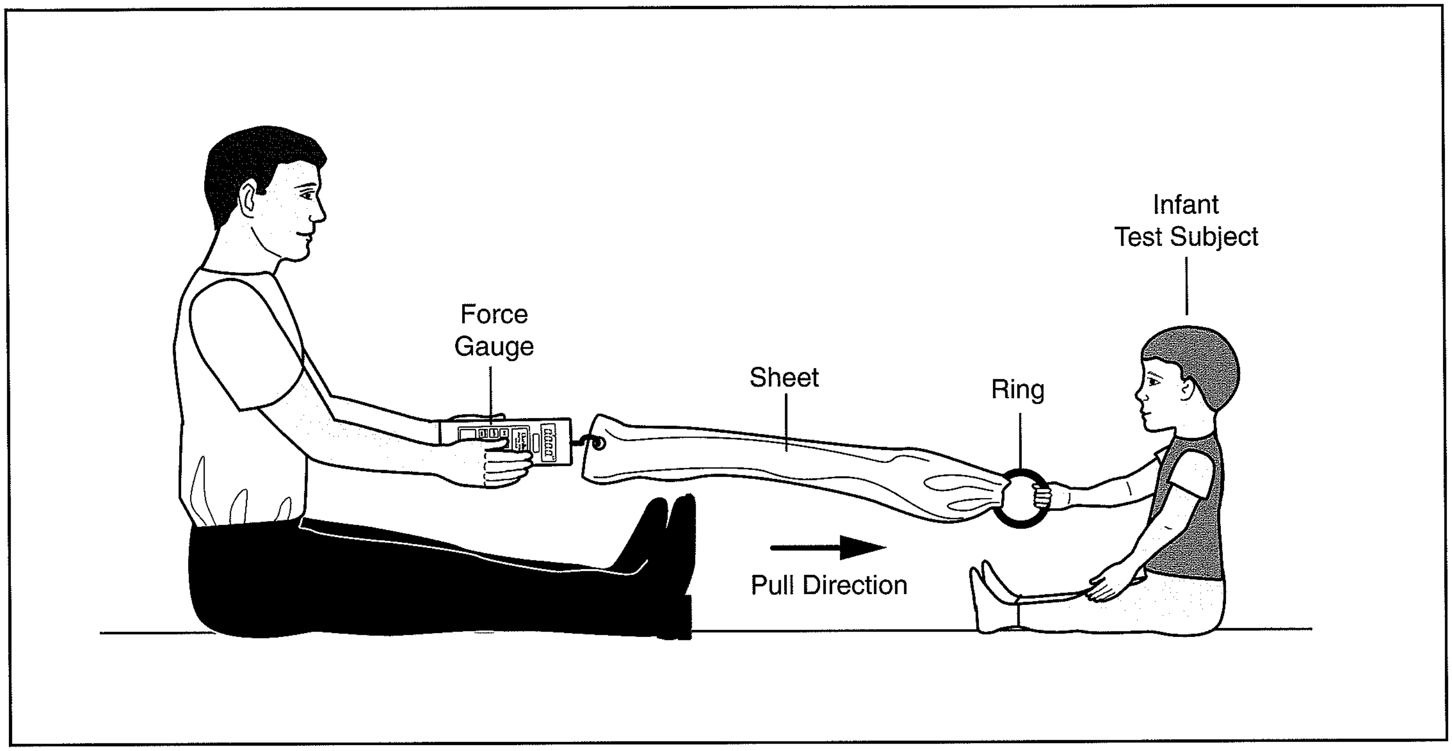

Figure 4 - Horizontal Pull Test

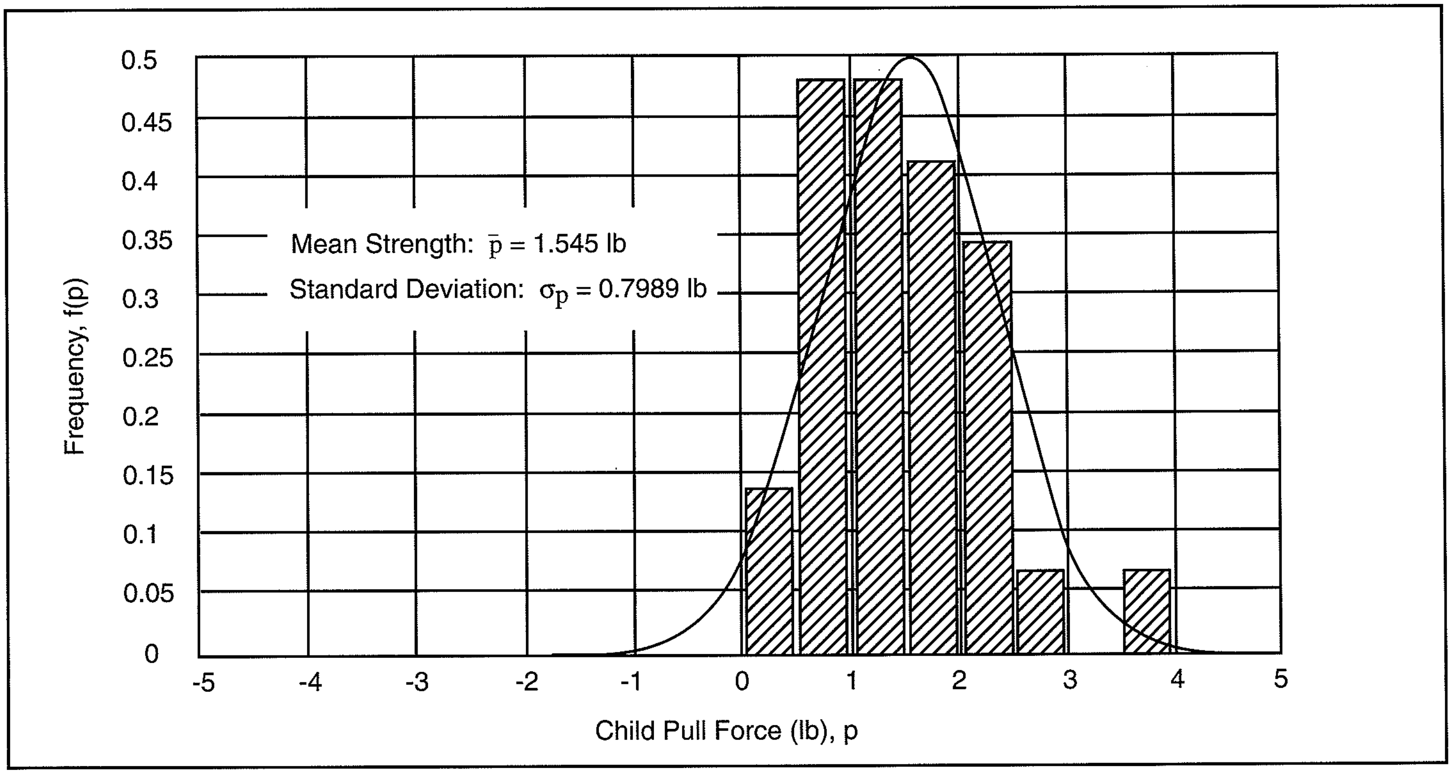

Figure 5 - Normal Probability Density and Relative Frequency Histogram

$$r - p \geq 0 \text{ ... no failure of the sheet}$$

If the resistance is normally distributed with mean $\bar{r}$ and standard deviation σ_r, and the loading is normally distributed with mean $\bar{p}$ and standard deviation σ_p, the difference of the two variates $\xi \equiv (r - p)$ is also a normal distribution $f(\xi)$ with mean $\bar{\xi}$ and standard deviation σ_ξ where

$$\bar{\xi} = \bar{r} - \bar{p}$$

and

$$\sigma_\xi = \sqrt{\sigma_r^2 + \sigma_p^2}$$

Figure 6 shows a normal probability density function for the difference quantity ξ. The area of the shaded portion of this figure represents the reliability of the fitted crib sheet, i.e.,

$$R = \int_0^\infty f(\xi)\, d\xi = 1 - \frac{1}{\sigma_\xi \sqrt{2\pi}} \int_{-\infty}^{0} e^{-\frac{1}{2}\left(\frac{\xi - \bar{\xi}}{\sigma_\xi}\right)^2} d\xi$$

$$= 1 - \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{-\frac{\bar{\xi}}{\sigma_\xi}} e^{-t^2/2} dt = \Phi\left(\frac{\bar{\xi}}{\sigma_\xi}\right)$$

where the tabulated standardized cumulative distribution function Φ for a normal distribution is defined as

$$\Phi\left(\frac{\xi - \bar{\xi}}{\sigma_\xi}\right) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\frac{\xi - \bar{\xi}}{\sigma_\xi}} e^{-t^2/2} dt \equiv \Phi(z)$$

and

$$\Phi(-z) = 1 - \Phi(z)$$

Example,

Resistance distribution: $\bar{r} = 7.7$ lb, $\sigma_r = 0.4$ lb

Load (Pull) distribution: $\bar{p} = 1.545$ lb, $\sigma_p = 0.7989$ lb

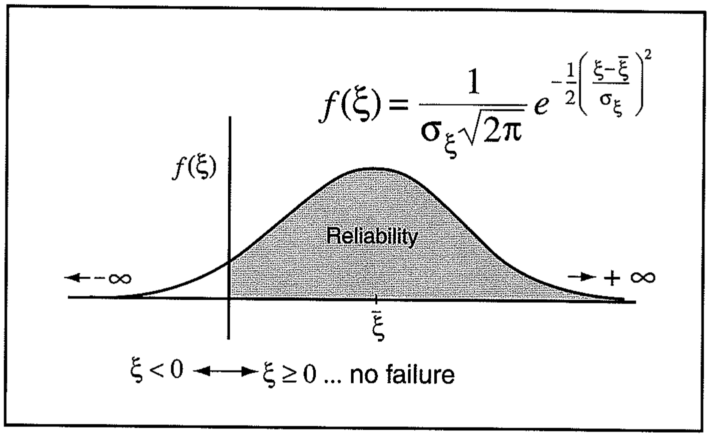

Figure 6 - Distribution of Difference Function $\xi = (r - p)$

$$\text{Reliability: } R = \Phi\left(\frac{\bar{\xi}}{\sigma_\xi}\right) = \Phi\left[\frac{(\bar{r} - \bar{p})}{\sqrt{\sigma_r^2 + \sigma_p^2}}\right]$$

$$= \Phi\left[\frac{(7.7 - 1.545)}{\sqrt{(0.4)^2 + (0.7989)^2}}\right] = \Phi(6.8891)$$

$$= 0.99999\ 99999\ 97175$$

This result demonstrates that the best sheet tested by GHI has a reliability of 100% when exposed to infants with perfect grips. Recall that this sheet, GHI sheet number 2, failed the GHI test standard.

CONCLUSIONS AND DISCUSSION OF RESULTS

1. The determined efforts of many organizations and safety practitioners have uncovered only two instances where infants were killed by mechanisms associated with fitted crib sheets. Both anecdotal accounts of these accidents have been challenged.
2. The accident frequency rate for fitted crib sheets is *de minimis*.
3. Using enhanced motivational and grip strength strategies, 33 infants were unable to remove the corners of a fitted crib sheet under conditions simulating the fatal accident of a 12 month old boy.
4. The "best" fitted crib sheet identified by the Good Housekeeping Institute has a zero probability of removal by infants using a power grip. This sheet will not pass the first proposed GHI fitted crib sheet standard.

5. All evidence suggests that the removal of the corners of fitted crib sheets by infants is not a foreseeable event. Consequently, by the doctrine of reasonable foreseeability (Ref. 28), the fitted crib sheet does not constitute a safety problem.

6. Society cannot sustain the costs of addressing safety nonproblems. It is a violation of the first canon of engineering ethics to promulgate solutions to such nonentities.

7. The pull strength of infants using a power grip is much smaller than the 44.5 *N* (10 lb) assumed by GHI based on toy standards.

8. Infants require a pinch-grip for removal of fitted crib sheets. It is our hypothesis that the pinch-grip mechanism is impoverished compared to the power-grip.

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